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Original article

The reliability of running economy among trained distance runners and field-based players

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Abstract

While the reliability of running economy (RE) has been widely established, limited investigation has been carried out into the reliability of various performance variables during a RE test. Subsequently, the purpose of the current study was to examine the reliability of time-to-exhaustion (TTE) and rating of perceived exertion (RPE) during a RE test among trained runners and moderately endurance-trained men. Absolute $\dot{V}O_2$ (mL/minute), $\dot{V}O_2$ relative to body mass (mL/kg/minute), oxygen cost of running (CR) defined as $\dot{V}O_2$ relative to body mass raised to the power of 0.75 per meter (ml kg$^{-0.75}$/m), heart rate (HR), ventilation ($\dot{V}_E$), carbon dioxide production ($\dot{V}CO_2$), respiratory exchange ratio and RPE were measured while treadmill running on two occasions at three discontinuous incremental speeds corresponding to 70%, 90%, and 110% of the second ventilatory threshold (VT_2). The duration of the last increment was measured as TTE. The reliability was determined using the intraclass correlation coefficient (ICC) and 95% ratio limits of agreement. The intraindividual variability was examined using the coefficient of variation (CV). There were no significant differences between the two RE trials for absolute $\dot{V}O_2$, relative $\dot{V}O_2$, CR, $\dot{V}_E$, $\dot{V}CO_2$, respiratory exchange ratio and RPE ($p \geq 0.05$) except for the differences in RPE during the first increment and the TTE ($p < 0.05$). The reliability was high for absolute $\dot{V}O_2$, relative $\dot{V}O_2$, CR, HR and TTE and was moderate for $\dot{V}_E$ and RPE. Small intraindividual variability was found for absolute $\dot{V}O_2$, relative $\dot{V}O_2$, CR, HR and RPE. The findings will enable sport scientists to incorporate a variety of performance variables when examining RE.
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Keywords: Physiology; Rating of perceived exertion; Running performance; Time to exhaustion

Introduction

The common method of assessing whether strenuous training sessions attenuate running performance in a randomized controlled trial is a running economy (RE) test.[1] The RE test has a high reliability[2] and a strong relationship to long-distance running performance.[3–5] A few studies have shown that RE is attenuated following down-hill running,[6,7] suggesting that the quality of a subsequent endurance training session may be compromised. A greater number of studies, however, have reported that RE is not affected several hours after strenuous exercises.[8–11] Subsequently, findings from these studies indicate that bouts of running sessions can be carried out a with minimal detriment in performance. Given that RE tests are conducted under anaerobic threshold (AT) for only 10–20 minutes,[1] drawing conclusions on running performance in response to strenuous exercise solely based on RE may be premature. In fact, a report[12] has shown that running sprint ability is impaired for 48 hours after repeated counter-movement jumps. These findings demonstrate that the ability to accurately detect changes in running performance may in part be dependent on the intensity of running performance.

Incorporating running at maximum effort as well as the rating of perceived exertion (RPE) in a RE test would improve

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the versatility of the protocol and broaden the interpretation of running performance following various experimental interventions. For example, Scott et al[11] found that RE was not affected 24–30 hours after lower extremity resistance exercises, although RPE did increase during submaximal running. Marcora and Bosio[9] also found that RE was not affected 48 hours after repeated vertical jumps, despite increases in creatine kinase and muscle soreness. The results showed that time-trial performance (TTP) worsened and that RPE was greater during submaximal running due to exercise-induced muscle damage. Collectively, these findings demonstrate that strenuous exercise increases the perception of effort at submaximal running and attenuates running performance at maximum effort. If Scott and colleagues[11] and Marcora and Bosio[9] had not incorporated performance parameters other than RE, however, their findings would have lead to alternative conclusions. Subsequently, RE tests may become more robust by incorporating RPE and running performance measures at maximum effort.

The TTP is reliable and effective as a complementary test protocol to a RE test.[13,14] The usability of such a protocol conducted at the completion of a RE test is questionable as it would require the runner to alter the running speed by hand, which would affect the economy of running unless a non-motorized treadmill is used. In addition, TTP would require further familiarity sessions due to complications associated with the setting of running speed. Time-to-exhaustion (TTE) may be a better indicator of running performance to maximum effort when conducted at the completion of a RE test, as the running speed is maintained during the protocol and the intensity would be identical between testing sessions. The reliability of RE at various intensities with a TTE protocol has not, however, been examined as far as the authors are aware.

Studies have shown that RE is highly reliable among small homogenous samples ($n = 4–8$) of elite or moderately-trained runners.[15–17] Homogenous samples are rarely available, however, and the practicality of such findings is limited to that specific cohort. Heterogeneous cohorts would allow access to a larger sample and provide research outcomes that can be applied to a wider demographic, but may result in high interindividual variability. One way to minimize this variability of RE is to quantify the oxygen cost of running (CR) expressed relative to body mass raised to the power of 0.75 per meter ($\dot{V}O_2$ mL kg$^{-0.75}$/m). For example, Helgerud[18] reported standard deviations of $\sim\pm8\%$ when CR was expressed relative to body mass ($\dot{V}O_2$ mL/kg/minute), whereas $\sim\pm5\%$ was found among junior soccer players[19] and trained distance runners[20] when expressed in $\dot{V}O_2$ mL kg$^{-0.75}$/m. While RE is expressed as absolute $\dot{V}O_2$ (mL/minute)[17] and relative $\dot{V}O_2$ (mL/kg/minute)[15] is reliable, little is known about the reliability of CR.

The purpose of the current study was to determine whether RPE and TTE are reliable when collected in conjunction with a RE test and to determine the reliability of CR at varying speeds among a heterogeneous cohort (i.e. trained and moderately endurance-trained runners).

Materials and methods

Participants

Seven trained male runners and seven moderately endurance-trained males (METMs) participated in the study (Table 1). The trained runners (TRs) were middle- to long-distance runners (1500–10,000 m) who had all run a 10,000 m time trial faster than 37 minutes during the past 6 months and who were all running at least 50 km/week throughout the duration of the study. The METMs had various sporting backgrounds (e.g., soccer, basketball and cricket) and were covering approximately 5–10 km/week. Each individual completed an informed consent form before taking part in any testing procedures. All procedures in this study were approved by the Institutional Human Research Ethics Committee and were run in accordance with the Declaration of Helsinki.

Research design

Following a familiarization session, the runners were tested over three separate sessions. A $\dot{V}O_{2max}$ test was conducted in the first session and the last two sessions each consisted of an identical RE test. The second ventilatory threshold (VT_2) was determined during the $\dot{V}O_{2max}$ test in order to ascertain the speed in which the subjects ran during the RE tests. At least 1 day of recovery between the $\dot{V}O_{2max}$ test and RE test and a minimum of 2 days and a maximum of 5 days of recovery between the two RE tests were provided, as it has been suggested that more than 1 day between repeated measures may be required to pre-empt bias from inadequate recovery.[21] Technical and biological variations were controlled by calibrating all measurement equipment, and requiring the runners to maintain their training intensity and volume throughout the course of the study, to wear the same shoes for every test, to refrain from high-intensity physical activity for at least 24 hours prior to testing and refrain from caffeine, food and supplement intake for at least 2 hours prior to testing.

Table 1
Physical characteristics of the trained and moderately endurance-trained runners.

Variables	Trained runners ($n = 7$)	Moderately endurance-trained runners ($n = 7$)
Age (years)	22 ± 4	23 ± 2
Height (m)	1.79 ± 0.09	1.82 ± 0.06
Mass (kg)	71.4 ± 8.5	75.8 ± 6.6
$\dot{V}O_{2max}$ (mL/kg/min)	69.42 ± 2.60	58.61 ± 3.23**
70% VT_2 (km/h)	11.64 ± 0.64	8.57 ± 1.25**
90% VT_2 (km/h)	14.93 ± 0.75	11.92 ± 1.22**
110% VT_2 (km/h)	18.31 ± 0.88	15.27 ± 1.42*
%$\dot{V}O_{2max}$ @ VT_2	88.29 ± 6.70	79.71 ± 4.03*
TTE (s)	336 ± 119	253 ± 88

Values are mean ± standard deviation.
*$p < 0.05$, **$p < 0.01$ (values significantly different from trained runners).
TTE = time to exhaustion from running economy test; $\dot{V}O_{2max}$ = maximal oxygen uptake; %$\dot{V}O_{2max}$ @ VT_2 = percentage maximal oxygen uptake at ventilatory threshold 2; VT_2 = ventilatory threshold 2.

Maximal oxygen uptake test

Prior to the $\dot{V}O_{2max}$ test, a progressive warm-up was completed by walking at 5 km/hour for 5 minutes then jogging at 8, 10, and 12 km/hour for 1 minute, respectively, at a continuous pace on a treadmill (Quinton Q65, Cardiac Science, USA, WI). The $\dot{V}O_{2max}$ test involved continuous incremental running in stages starting at 12 km/hour, and increasing the speed by 1.5 km/hour every minute until exhaustion. The gradient was kept at 0% throughout the test. This particular $\dot{V}O_{2max}$ test was deemed appropriate for the current runners given that it was previously used on a similar endurance-trained cohort.[22] Heart rate (HR; measured using the Polar RS800, Polar, New York, USA) and RPE (Borg's 6–20 point scale) were recorded every minute. Expired air samples were analyzed with a Cosmed K4b^2 gas analyzer (Cosmed, Rome, Italy). The flow meter was calibrated with a 3-L calibration syringe and a reference air calibration of the system was performed using a certified alpha gas mixture containing 16% O_2 and 4% CO_2. Data were measured breath-by-breath and the respiratory variables averaged every 15 seconds.[23] The highest average $\dot{V}O_2$ value over a 15-second interval was accepted as $\dot{V}O_{2max}$ when the individual met three of the four criteria: $\dot{V}O_2$ plateau, RPE >17, respiratory exchange ratio (RER) >1.1, peak HR >90% of age-predicted HR.[24] The VT_2 for each individual was determined by identifying the inflection point of $\dot{V}_E$ with respect to $\dot{V}CO_2$ on a scatter diagram.[25]

Running economy test with time to exhaustion

The warm-up for the RE test was identical to the $\dot{V}O_{2max}$ test. The RE protocol was a three-stage discontinuous incremental test to exhaustion. A 2-minute passive recovery period was given between each stage. The running speed was set at 70, 90 and 110% of VT_2 for the three stages, respectively. The duration of the first two stages was set at 10 minutes each and the individuals ran until exhaustion during the last stage to determine TTE, which was considered as an additional performance variable in conjunction with the physiological parameters. The VT_2 was used due to its greater reliability[23] and ability to induce the onset of fatigue earlier than the first ventilatory threshold (VT_1).[26] The physiological variables of $\dot{V}O_2$, $\dot{V}_E$, HR and RER were averaged during the last 5 minutes of each of the first two stages to ensure the individuals reached steady state. Steady state was defined when the change in $\dot{V}O_2$ was <10%.[27] The $\dot{V}O_2$ values between the 5th and 10th minute of each of the first two stages were compared to ascertain any possible existence of $\dot{V}O_2$ slow component.[28]

The physiological variables for the last stage were averaged over the last minute as some individuals were unable to run for longer than 5 minutes. The aerobic demand of running was expressed as absolute $\dot{V}O_2$ (L/minute), relative $\dot{V}O_2$ (mL/kg/minute) and CR (mL kg$^{-0.75}$/m). RPE was recorded 1 minute prior to the end of the first and second stages. During the third stage, RPE was recorded every 30 seconds and the last RPE prior to exhaustion was then selected as perceived exertion.

Statistical analysis

Measures of centrality and spread are shown as mean ± between-subject standard deviation. All data were analyzed using the Statistical Package for Social Sciences (SPSS, version 18, Chicago, IL, USA). The intraclass correlation coefficient (ICC, SPSS two-way mixed with 95% confidence intervals) was used to assess both systematic and random errors that might affect relative test–retest reliability of the physiological and performance variables. The measurement of absolute reliability was expressed using measurement bias/ratio with 95% limits of agreement (LOA).[29] The coefficient of variation (CV) (95% confidence limits) was determined according to an Excel spreadsheet.[30] The relationship between the absolute differences and the mean of the variables was positive and therefore data were found to be heteroscedastic (an example is depicted in Fig. 1), thus all data were transformed using natural logarithms before calculating ratio limits of agreement.[31] The differences between the two RE trials for all variables and $\dot{V}O_2$ between the 5th and 10th minute of the first two stages were analyzed using paired *t* tests whereas the between-group differences in the physical characteristics for TRs and METMs were examined using independent *t* tests. Statistical significance was established at the 0.05 level.

Results

The $\dot{V}O_{2max}$ (ml/kg/minute), running speeds at 70%, 90% and 110% of VT_2, and percentage of $\dot{V}O_{2max}$ at VT_2 were significantly greater for TRs than METMs ($p < 0.05$; see Table 1). There were no significant differences in age, height, body mass and TTE ($p \geq 0.05$) between TRs and METMs.

Steady-state $\dot{V}O_2$ was achieved within 3 minutes of the commencement of the first and second stages of Trials 1 and 2. No significant differences were found for $\dot{V}O_2$ between the 5th and 10th minute during the first two stages of Trials 1 and 2 ($p \geq 0.05$), with the largest difference being 0.86 mL/kg/minute, eliminating the possibility that a $\dot{V}O_2$ slow component exists.

No significant differences were found for: CR, absolute $\dot{V}O_2$, relative $\dot{V}O_2$, $\dot{V}_E$, $\dot{V}CO_2$, RER and HR during stage 1

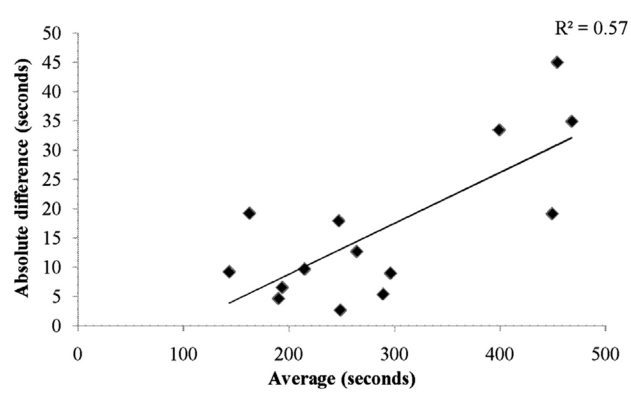

Fig. 1. Bland and Altman Plot of the absolute difference between trials 1 and 2 against the mean of trials 1 and 2.

($p \geq 0.05$); CR, absolute $\dot{V}O_2$, relative $\dot{V}O_2$, $\dot{V}_E$, $\dot{V}CO_2$, RER, HR and RPE during stage 2 ($p \geq 0.05$); and during TTE ($p \geq 0.05$) between RE trial 1s and 2 (Table 2). Variables that were significantly greater during RE trial 1 compared to trial 2 included RPE during stage 1 ($p < 0.05$) and TTE ($p < 0.01$).

The ICC between both trials of each incremental stage of the RE test for absolute $\dot{V}O_2$, relative $\dot{V}O_2$, CR, $\dot{V}_E$, $\dot{V}CO_2$, RER, HR, and RPE ranged from 0.90 to 0.95, 0.93 to 0.96, 0.90 to 0.92, 0.73 to 0.84, 0.64 to 0.78, 0.08 to 0.35, 0.93 to 0.97, and 0.69 to 0.85, respectively (Table 3). Similarly, the measurement bias ratio for absolute $\dot{V}O_2$, relative $\dot{V}O_2$, CR, $\dot{V}_E$, $\dot{V}CO_2$, RER, HR and RPE ranged from 1.02 to 1.03, 1.01 to 1.02, 1.01, 1.00 to 1.02, 1.01, 0.98 to 0.99, 1.01 to 1.03, and 0.98 to 1.06, respectively. The CV for absolute $\dot{V}O_2$, relative $\dot{V}O_2$, CR, $\dot{V}_E$, $\dot{V}CO_2$, RER, HR and RPE ranged from 2.4 to 3.1, 2.2 to 2.9, 2.2 to 2.9, 4.8 to 5.3, 4.9 to 7.9, 4.2 to 6.1, 0.9 to 1.8, and 3.1 to 4.3, respectively.

Table 2
Physiological variables averaged during the last 5 minutes of each of the first two stages and the last minute of the third (time-to-exhaustion) stage of the running economy test.

Variables	RE Trial 1	RE Trial 2	Δ RE Trial 1−2
$\dot{V}O_2$ (L/min)			
First stage	3.34 ± 0.35	3.25 ± 0.28	0.09 ± 0.15
Second stage	4.22 ± 0.53	4.12 ± 0.42	0.10 ± 0.24
Third stage	4.71 ± 0.56	4.61 ± 0.49	0.10 ± 0.18
$\dot{V}O_2$ (mL/kg/minute)			
First stage	45.25 ± 4.61	44.35 ± 3.59	0.90 ± 0.93
Second stage	56.75 ± 6.86	56.04 ± 6.03	0.71 ± 1.31
Third stage	62.99 ± 7.03	62.31 ± 6.93	0.68 ± 1.10
CR (mL kg$^{-0.75}$/m)			
First stage	0.75 ± 0.07	0.73 ± 0.06	0.02 ± 0.01
Second stage	0.73 ± 0.06	0.72 ± 0.07	0.01 ± 0.01
Third stage	0.66 ± 0.04	0.65 ± 0.05	0.01 ± 0.01
$\dot{V}_E$ (mL/min)			
First stage	76.90 ± 7.73	75.51 ± 7.29	1.39 ± 5.68
Second stage	111.96 ± 13.23	108.63 ± 12.24	3.32 ± 7.78
Third stage	149.20 ± 16.34	149.02 ± 19.30	0.18 ± 10.18
$\dot{V}CO_2$ (L/min)			
First stage	3.10 ± 0.36	3.08 ± 0.29	0.02 ± 0.04
Second stage	4.09 ± 0.60	4.04 ± 0.47	0.05 ± 0.09
Third stage	4.96 ± 0.82	4.88 ± 0.65	0.08 ± 0.12
RER			
First stage	0.94 ± 0.03	0.95 ± 0.04	−0.01 ± 0.06
Second stage	0.99 ± 0.04	1.00 ± 0.05	−0.01 ± 0.07
Third stage	1.06 ± 0.05	1.08 ± 0.07	−0.02 ± 0.09
HR (beats/min)			
First stage	151.64 ± 10.72	149.78 ± 11.04	1.86 ± 6.08
Second stage	176.08 ± 10.37	174.78 ± 9.88	1.30 ± 4.00
Third stage	190.57 ± 9.08	189.74 ± 9.18	0.83 ± 2.69
RPE			
First stage	11.07 ± 1.00	10.57 ± 1.02*	0.50 ± 0.65
Second stage	14.57 ± 1.65	14.86 ± 1.66	−0.29 ± 0.91
Third stage	18.57 ± 1.50	18.79 ± 1.48	−0.22 ± 0.89
TTE (s)			
Third stage	265 ± 113	279 ± 130	13 ± 9.75

Values are mean ± standard deviation.
*$p < 0.05$ values significantly different between the first and second RE trials.
CR = oxygen cost of running; HR = heart rate; RER = respiratory exchange ratio; RPE = rating of perceived exertion; TTE = time-to-exhaustion; $\dot{V}_E$ = ventilation; $\dot{V}O_2$ = oxygen uptake.

Discussion

The major findings in the current study are that TTE and RPE were reliable when conducted as part of a RE test. In addition, various physiological variables were reliable at different intensities of VT_2 whereas the reliability for $\dot{V}CO_2$ and RER were questionable among a heterogeneous cohort. As expected the $\dot{V}O_{2max}$ and running speed were significantly greater for the TRs than the METMs, which provides a heterogeneous sample when pooled for reliability analyses.

Reliability and intraindividual variability of time-to-exhaustion and rating of perceived exertion

According to the results, RPE showed moderate reliability across the three stages (ICC = 0.82−0.89) and CV varied from 3.1% to 4.3%. While there are no previous reports indicating the reliability of RPE for RE tests combined with TTE to the authors' knowledge, Doherty et al[32] did examine the reliability of perceived exertion using Borg's RPE scale during treadmill running to exhaustion and showed a moderate reliability (ICC = ∼0.82) at four different time points. Moreover, Doherty et al[32] reported that the possible difference in RPE between the two trials should lie within ∼0 ± 2 according to the LOA (95%). Accordingly, the LOA for RPE from the current study was approximately 1.01 */÷ 1.07 for the three stages, indicating that an RPE of 20 or below would fall within the range of ± 2, which agrees with that reported by Doherty et al.[32]

The TTE across RE trials 1 and 2 showed high reliability (ICC = 0.94), with a mean difference of 13 seconds. These results demonstrate higher reliability than previous reports for running TTE at intensities equivalent to 1500 m and 5 km distances (ICC = 0.46 and 0.57, respectively)[13] and with running TTE at 95% and 90% of $\dot{V}O_{2max}$ (ICC = 0.80 and 0.75, respectively).[33] TTE did indicate greater within-subject variability (CV = 9.2%) across RE Trials 1 and 2 compared to the other variables that have demonstrated equal reliability (i.e., $\dot{V}O_2$ and HR). The variability for TTE in the current study is smaller, however, than reports given by Billat et al (CV = 25%)[16] and Harling et al (CV = 15%)[34] with running TTE at $\dot{V}O_{2max}$, and by Hickson et al[35] with running speeds adjusted to elicit exhaustion with durations of approximately 2, 4, and 8 minutes (CV = 9.2%, 13%, and 16%, respectively). While TTE in the current study showed high reliability that appears to be more acceptable than that of previous reports, the LOA indicated questionable agreements (95% LOA = 0.99 */÷ 1.18). The high reliability in contrast to a questionable agreement may be a result of sample heterogeneity.[21] Nonetheless, the incorporation of TTE in a RE test may be useful, as indicated by the within-subject variability (CV = 9.2%) being less than that of the previous literature.[16,34,35] In addition, while the aerobic demand of RE as an indication of running performance is well established, TTE provides a more practical measurement of monitoring athletes' training or assessing whether running performance is affected by an intervention.

Table 3
Intraclass correlation coefficients with 95% confidence interval, measurement bias/ratio (log-transformed data) */÷ 95% ratio limits of agreement and typical error of measurement as a coefficient of variation (95% confidence limits) of physiological variables and time-to-exhaustion.

	Intraclass correlation coefficients (95% confidence interval)	Measurement bias/ratio (*/÷ 95% ratio LOA)	Coefficient of variation (%) (95% confidence limits)
$\dot{V}O_2$ (L/min)			
First stage	0.90 (0.73−0.97)**	1.03 */÷ 1.08	2.9 (2.2−4.3)
Second stage	0.91 (0.74−0.97)**	1.02 */÷ 1.09	3.1 (2.4−4.6)
Third stage	0.95 (0.84−0.98)**	1.02 */÷ 1.07	2.4 (1.8−3.6)
$\dot{V}O_2$ (mL/kg/min)			
First stage	0.93 (0.79−0.98)**	1.02 */÷ 1.07	2.3 (1.8−3.5)
Second stage	0.93 (0.80−0.98)**	1.01 */÷ 1.08	2.9 (2.2−4.3)
Third stage	0.96 (0.89−0.99)**	1.01 */÷ 1.06	2.2 (1.7−3.3)
CR (mL $kg^{-0.75}$/m)			
First stage	0.92 (0.77−0.97)**	1.01 */÷ 1.07	2.5 (1.9−3.7)
Second stage	0.90 (0.75−0.97)**	1.01 */÷ 1.08	2.9 (2.2−4.4)
Third stage	0.91 (0.75−0.97)**	1.01 */÷ 1.06	2.2 (1.7−3.3)
$\dot{V}_E$ (mL/min)			
First stage	0.73 (0.32−0.90)*	1.02 */÷ 1.16	5.3 (4.0−7.8)
Second stage	0.82 0.52−0.94)**	1.03 */÷ 1.15	5.0 (3.8−7.4)
Third stage	0.86 (0.57−0.95)**	1.00 */÷ 1.14	4.8 (3.7−7.2)
$\dot{V}CO_2$ (L/min)			
First stage	0.78 (0.45−0.92)**	1.01 */÷ 1.14	4.9 (3.7−7.4)
Second stage	0.64 (0.18−0.87)**	1.01 */÷ 1.24	7.9 (6.0−12)
Third stage	0.76 (0.39−0.91)**	1.01 */÷ 1.23	7.7 (5.8−11.6)
RER			
First stage	0.08 (−0.57−0.46)	0.98 */÷ 1.12	4.2 (3.2−6.3)
Second stage	0.35 (−0.43−0.59)	0.99 */÷ 1.14	4.7 (3.6−7.0)
Third stage	0.17 (−0.50−0.53)	0.98 */÷ 1.18	6.1 (4.6−9.0)
HR (beats/min)			
First stage	0.84 (0.58−0.95)**	1.01 */÷ 1.03	2.9 (2.2−4.3)
Second stage	0.92 (0.78−0.97)**	1.00 */÷ 1.02	1.6 (1.2−2.4)
Third stage	0.96 (0.87−0.99)**	1.00 */÷ 1.02	1.0 (0.8−1.5)
RPE			
First stage	0.82 (0.59−0.93)**	1.06 */÷ 1.09	3.4 (2.6−5.0)
Second stage	0.85 (0.59−0.95)**	0.98 */÷ 1.06	4.3 (3.3−6.5)
Third stage	0.89 (0.66−0.94)**	1.00 */÷ 1.06	3.1 (2.3−4.6)
TTE (s)			
Third stage	0.94 (0.81−0.98)**	0.99 */÷ 1.18	9.2 (4.7−15.6)

*$p < 0.01$, **$p < 0.001$.
CR = oxygen cost of running; HR = heart rate; LOA = limits of agreement; RER = respiratory exchange ratio; RPE = rating of perceived exertion; TTE = time-to-exhaustion, $\dot{V}O_2$ = oxygen uptake; $\dot{V}_E$ = ventilation.

Reliability and intraindividual variability of the oxygen cost of running

The CR, absolute $\dot{V}O_2$ and relative $\dot{V}O_2$ showed no significant differences between RE Trials 1 and 2 for the three stages with low percentages of CV, which confirms the results of previous studies.[2,15,17] The ratio LOA for CR, absolute $\dot{V}O_2$ and relative $\dot{V}O_2$ (*/÷ 95% ratio) ranged from 1.06 to 1.09, indicating that the difference in energy cost between the two RE trials due to inaccurate measurement and biological error will typically be neither more nor less than 6−9%. This demonstrates a narrow LOA and small within-subject variability across the two RE trials for the three stages.

Directly comparing the intraindividual variability from the current study with literature is at present difficult, as studies have not yet assessed the agreement between measurements of the aerobic demand of RE according to the technique devised by Bland et al.[29] However, the results from the current study are similar to that reported for outrigger canoeing (LOA = 1.08−1.09)[23] and smaller than that for arm crank ergometry (LOA = 1.11−1.12).[36] Sealey et al[23] and Leicht et al[36] reported $\dot{V}O_2$ as peak values that are not indicative of CR. Nevertheless, the agreement ratios of the RE test for the current study were close to 1.06, which is regarded as excellent.[31]

The absolute $\dot{V}O_2$, relative $\dot{V}O_2$ and CR indicated high reliability (ICC = 0.90−0.97) for RE across the two trials and confirms the results by Morgan et al[17] for the aerobic demand of RE (ICC = 0.95). While the protocols used in the current study and that by Morgan and coauthors[17] are different, with Morgan and colleagues[17] conducting a continuous running protocol and incorporating a homogenous group of trained distance runners, the similarities in the aerobic demand from the two RE trials demonstrates that the RE test in the current study is reliable among a heterogeneous cohort at various speeds. Moreover, the greater reliability and lesser intraindividual variability for CR and relative $\dot{V}O_2$ compared to absolute $\dot{V}O_2$ demonstrates that the stability of the protocol is greater by expressing the aerobic demand in relative terms.

Reliability and intraindividual variability of heart rate, ventilation, carbon dioxide production and respiratory exchange ratio

In contrast to the CR in the current study, $\dot{V}_E$ and RER showed a larger variation ranging from 4.8% to 5.3% and from 4.2% to 6.1%, respectively. The CV for HR ranged from 1.0% to 2.9%, however, showing smaller variability than the CR. These results are similar to Saunders et al,[2] who measured CV between two RE trials for $\dot{V}_E$ (6.6–8.3%), HR (1.7–2.4%) and RER (3.4–4.4%) at varying speeds. Pereira and colleagues[15] showed no significant differences for $\dot{V}_E$, HR and RER between two RE trials at a continuous speed, but the variability was not measured. In the current study, the reliability was moderate to high for HR (ICC = 0.84–0.96, LOA = 1.02–1.03) and questionable for RER (ICC = 0.08–0.35, LOA = 1.14–1.16) and $\dot{V}CO_2$ (ICC = 0.64–0.78, LOA = 1.14–1.24) for each of the three stages and moderate for $\dot{V}_E$ (ICC = 0.82–0.86, LOA = 1.12–1.18) during the last two stages. The low ICC values for RER may be attributed to the questionable reliability of $\dot{V}CO_2$, which is similar to findings by Leicht et al[36] during arm crank ergometry. While the usability of $\dot{V}CO_2$ appears to be of concern, the incorporation of RER may still be an effective means of assessing running performance across trials as the intraindividual variability was similar to $\dot{V}_E$ and TTE, which had greater reliability. However, further assessment on the variability of RER across a greater number of RE trials is warranted.

Interindividual variability amongst a heterogeneous cohort

While investigation of the repeatability of RE among a heterogeneous cohort is limited, Pereira et al[37] reported small intraindividual variability separately for highly- and moderately-trained males (CV = 1.77% and 2.00%, respectively) across two RE trials. Morgan and colleagues[17] also showed similar intraindividual variability in submaximal running for male and female distance runners (CV = ~1.76% and 1.78%, respectively) despite differences of ~10ml kg^{-1}/minute in $\dot{V}O_{2max}$ between genders. Such findings indicate that fitness levels and training backgrounds may have minimal impact on the intraindividual variability of RE across trials.

While the intraindividual variability was minimal in the current study, the interindividual variability would be of concern among trained and moderately-trained individuals, and subsequently affect the power of statistical analyses. As demonstrated, the interindividual variability for absolute $\dot{V}O_2$ (L/minute) and relative $\dot{V}O_2$ (mL/kg/minute) between RE Trials 1 and 2 was ~10–11%. When the CR was expressed as $\dot{V}O_2$ mL $kg^{-0.75}$/m, however, the interindividual variability was reduced to ~8%, which is less than the studies that incorporated homogenous samples and reported the aerobic demand for RE expressed relative to body mass (mL/kg/minute).[15,16] Although Helgerud and colleagues[19,20] have shown interindividual variation of ≤5%, the current study demonstrates that interindividual variability can be minimized when the aerobic demand for RE is expressed as CR ($\dot{V}O_2$ mL $kg^{-0.75}$/m) rather than absolute or relative $\dot{V}O_2$ (mL/minute or mL/kg/minute, respectively). Subsequently, it is recommended that the aerobic demand of RE relative to body mass is expressed as raised to the power of 0.75/meter in order to control interindividual variability.

Conclusion

In conclusion, numerous physiological and performance variables are reliable during RE at various running speeds among a heterogeneous cohort. This suggests that small changes in the physiological variables within the current protocol may be sufficient to indicate attenuation of running performance as a result of a particular intervention.

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